Casimir Corrections and Laboratory Tests of Vacuum Granularity

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Abstract

Within the Granular Cosmic Vacuum (GCV) framework, the intergalactic domain P_2 is not a smooth quantum-field-theoretic vacuum, but a lattice of microscopic white holes (MWs) stabilized by contracted temporal strings. Earlier work in this series identified dark energy with the tension of a closed cosmic temporal string in P_2 and dark matter with the pressure of closed spatial membranes in the halo domain P_3. In this fourth component, we analyze how vacuum granularity manifests in high-precision Casimir experiments, and how such laboratory tests can be combined with high-energy gamma-ray observations to probe the same underlying length scale of the granular vacuum.

We show that the discretization of allowed electromagnetic modes in a granular vacuum leads to a small correction to the standard Casimir force between parallel plates. For plate separation d and granule spacing ℓ_g, the total force per unit area can be written as

$$F_{\rm total}(d) = F_{\rm Cas}(d)\,[\,1+\delta_{\rm gran}(d)\,], \qquad F_{\rm Cas}(d) = -\frac{\pi^2\hbar c}{240\,d^4},$$

with a relative correction

$$\delta_{\rm gran}(d) = \kappa\left(\frac{d}{\ell_g}\right)^n, \quad n>0,\ \kappa \ll 1.$$

The structural exponent n and amplitude κ depend on the geometry and tension of the underlying lattice of microscopic white holes. We relate κ to the Planck tension $T_{\rm P} = c^5/(G\ell_{\rm P})$ and the structural-damping parameter $\lambda_{\rm struct}$ that also appear in the dark-energy and dark-matter components of the GCV model. The same granule length ℓ_g enters the extra attenuation factor for high-energy gamma rays in P_2, providing a direct astrophysical–laboratory consistency check.

Using present Casimir measurements with relative precision at the level of 10^{-2}–10^{-3} in the range $d \sim 100$–$1000\,$nm, we obtain a conservative lower bound $\ell_g \gtrsim 10^{-19}\,$m for typical choices $n \simeq 1$ and $\kappa \sim 10^{-6}$ suggested by the structural-damping hierarchy. We outline how cryogenic measurements, superconducting resonators, and "Casimir-less" configurations could improve these bounds by one to two orders of magnitude. In parallel, constraints on the gamma-ray attenuation parameter γ_N from Fermi-LAT and future Cherenkov Telescope Array (CTA) observations can be translated into independent bounds on ℓ_g.

Throughout we stress that the "strings" and "membranes" of the GCV are classical geometric entities in four-dimensional spacetime, *not* superstrings or higher-dimensional branes. They do not possess quantized vibrational spectra or supersymmetry; their role is purely structural, encoding Planck-scale tension and its hierarchical damping. Casimir corrections and gamma-ray data thus provide a falsifiable test of vacuum granularity rooted in classical geometry rather than superstring dynamics.

Keywords— Casimir effect; granular vacuum; granular cosmic vacuum; microscopic white holes; Planck tension; structural damping; gamma-ray attenuation; dark sector; high-precision experiments.

1 Introduction

The Casimir effect is one of the most sensitive experimental probes of the quantum vacuum. In its standard formulation, two parallel, perfectly conducting plates separated by a distance d experience an attractive force due to the altered spectrum of zero-point fluctuations of the electromagnetic field between them. For ideal plates in a smooth vacuum, the force per unit area is

$$F_{\rm Cas}(d) = -\frac{\pi^2 \hbar c}{240\, d^4}, \tag{1}$$

where d is assumed to be large compared to any microscopic cutoff such as the Planck length $\ell_{\rm P}$.

Modern experiments have confirmed Eq. (1) to high precision, including realistic corrections from finite conductivity, surface roughness and thermal effects. At the same time, measurements at sub-micrometer separations have been used to constrain hypothetical new interactions and to test ideas about extra dimensions or modified gravity.

In the Granular Cosmic Vacuum (GCV) framework, the vacuum is not a featureless continuum at all scales. Rather, the universe is divided into three structural domains:

- P_1, galactic interiors, where standard General Relativity (GR) and Quantum Field Theory (QFT) apply.
- P_2, the intergalactic desert, where the vacuum is a granular medium composed of microscopic white holes (MWs) stabilized by contracted temporal strings.
- P_3, galactic halos, where closed spatial membranes generate effective gravitational fields that mimic dark matter.

Earlier papers in this series developed the GCV architecture and identified dark energy with the tension of a closed cosmic temporal string in P_2, and dark matter with the pressure of closed spatial membranes in P_3.

In this paper, we ask: *if the vacuum is granular in P_2, how should this be seen in Casimir experiments, and how can those laboratory tests be combined with astrophysical gamma-ray data to probe the same granular structure?* We show that vacuum granularity naturally introduces a correction factor $\delta_{\rm gran}(d)$ to the Casimir force, and that its dependence on d and on the granule scale ℓ_g is tightly tied to the same Planck-tension and structural-damping parameters that control the dark sector.

A central conceptual point is that all "strings" and "membranes" in the GCV are classical geometric objects in four-dimensional spacetime. They are not superstrings or supermembranes:

- They live in ordinary $3+1$ dimensions.
- They do not have quantized vibrational modes or a tower of particle states.
- They do not require supersymmetry or higher-dimensional target spaces.

All observable effects—dark energy, dark-matter-like halos, gamma-ray attenuation, and Casimir corrections—arise from classical geometry and tension, not from superstring theory.

2 The GCV framework and Planck-scale tension

In the GCV picture, the microscopic building blocks of the intergalactic vacuum in P_2 are microscopic white holes (MWs). Each MW is stabilized by three contracted temporal strings, one associated (at a structural level) with each of the pure interaction sectors: electromagnetic, strong and weak. A ternary composition rule ($3 \to 1$) combines these contracted strings into effective closed temporal strings, and, on cosmological scales, they merge into a single closed cosmic temporal string that encodes the global structure of time in P_2.

The natural microscopic scale for tension in this network is the Planck tension,

$$T_{\rm P} = \frac{c^5}{G\ell_{\rm P}} \sim 10^{70}\,{\rm J\,m^{-1}}, \tag{2}$$

with $\ell_{\rm P} \approx 1.6 \times 10^{-35}\,{\rm m}$ the Planck length. However, the observed dark-energy density is much smaller. Paper 2 introduced a structural-damping mechanism that reduces $T_{\rm P}$ to an effective cosmic tension,

$$T_{\rm cosmic} = T_{\rm P} \left(\frac{R_H}{\ell_{\rm P}}\right)^{-\lambda_{\rm struct}}, \qquad 0 < \lambda_{\rm struct} < 1, \tag{3}$$

where $R_H = c/H_0$ is the Hubble radius. The associated dark-energy density is

$$\rho_\Lambda = \frac{T_{\rm cosmic}}{R_H} \approx 10^{-9}\,{\rm J\,m^{-3}}, \tag{4}$$

in agreement with observations, without summing QFT zero-point modes or invoking fine-tuned cancellations.

The same structural-damping paradigm appears in the membrane model of dark matter (Paper 3), where closed spatial membranes in P_3 carry an internal tension inherited from $T_{\rm P}$, damped to produce membrane pressures that mimic cold dark matter at galactic scales.

In what follows, we link the Casimir correction amplitude κ to $T_{\rm P}$, $T_{\rm cosmic}$, and $\lambda_{\rm struct}$, showing that Casimir experiments test the same deep structure that underlies both dark energy and dark matter in the GCV framework.

3 Standard Casimir effect in a smooth vacuum

For two parallel, perfectly conducting plates separated by distance d in a smooth vacuum, the allowed electromagnetic modes between the plates have discrete wave-vector components perpendicular to the plates and continuous components parallel to them. The zero-point energy per unit area can be expressed as

$$E_0(d) = \frac{\hbar c}{2} \int \frac{d^2k_\parallel}{(2\pi)^2} \sum_{m=1}^{\infty} \sqrt{k_\parallel^2 + \left(\frac{m\pi}{d}\right)^2}, \tag{5}$$

where $k_\parallel$ is the two-dimensional wave vector parallel to the plates, and m labels the discrete standing-wave modes in the perpendicular direction.

Subtracting the vacuum energy with no plates and regularizing the resulting difference yields the well-known Casimir energy and force. The force per unit area is

$$F_{\mathrm{Cas}}(d) = -\frac{\partial E_0(d)}{\partial d} = -\frac{\pi^2 \hbar c}{240\, d^4}. \tag{6}$$

This result assumes that space is continuous in all directions, with no intrinsic granular cutoff apart from the implicit ultraviolet regularization.

4 Granular modification of the Casimir spectrum

4.1 Discrete k-space from vacuum granularity

In a granular vacuum with granule spacing ℓ_g, the allowed transverse wave vectors can be modeled as a discrete lattice in k-space:

$$k_x = \frac{2\pi}{\ell_g} n_x, \quad k_y = \frac{2\pi}{\ell_g} n_y, \qquad n_x, n_y \in \mathbb{Z}. \tag{7}$$

The continuum integral over $k_\parallel$ is replaced by a double sum,

$$\int \frac{d^2k_\parallel}{(2\pi)^2} \quad \longrightarrow \quad \frac{1}{\ell_g^2} \sum_{n_x, n_y = -\infty}^{\infty}. \tag{8}$$

The zero-point energy between the plates becomes

$$E_{\mathrm{gran}}(d) = \frac{\hbar c}{2\ell_g^2} \sum_{n_x, n_y = -\infty}^{\infty} \sum_{m=1}^{\infty} \sqrt{\left(\frac{2\pi}{\ell_g}\right)^2 (n_x^2 + n_y^2) + \left(\frac{m\pi}{d}\right)^2}. \tag{9}$$

As in the standard case, one subtracts the corresponding energy with no plates to obtain the finite vacuum-energy difference. The resulting expression can be written as

$$E_{\mathrm{gran}}(d) = E_0(d)\,[1 + \delta_{\mathrm{gran}}(d)]\,, \tag{10}$$

where $E_0(d)$ is the standard Casimir energy and $\delta_{\mathrm{gran}}(d)$ encodes the effect of vacuum granularity.

4.2 Form of the correction

For experimental separations $d \gg \ell_g$, a systematic expansion in the small parameter (ℓ_g/d) leads to a leading-order correction of the form

$$\delta_{\rm gran}(d) = \kappa \left(\frac{d}{\ell_g}\right)^n, \qquad n > 0,\ \kappa \ll 1. \tag{11}$$

The total Casimir force per unit area is therefore

$$F_{\rm total}(d) = F_{\rm Cas}(d)\,[1 + \delta_{\rm gran}(d)] = -\frac{\pi^2 \hbar c}{240\, d^4}\left[1 + \kappa \left(\frac{d}{\ell_g}\right)^n\right]. \tag{12}$$

Here n is a structural exponent determined by the geometry of the MW lattice and the effective boundary conditions imposed by the plates, while κ is a dimensionless amplitude that depends on the ratio of Planck-scale tension to the cosmic tension and on the details of structural damping.

For a simple cubic lattice and natural assumptions about mode counting, one typically finds n of order unity (e.g., $n \simeq 1$), but the formalism allows for other values.

5 Linking κ to Planck tension and structural damping

The effective correction amplitude κ is expected to be small because the observed dark-energy density is much smaller than the Planck density. A simple estimate uses the same structural-damping logic that led from $T_{\rm P}$ to $T_{\rm cosmic}$.

Let $\xi \equiv \ell_g/\ell_{\rm P} > 1$ be the ratio of the granule scale to the Planck length. For $d \gg \ell_g$ we can write

$$\kappa \sim \left(\frac{\ell_{\rm P}}{\ell_g}\right)^n \left(\frac{T_{\rm cosmic}}{T_{\rm P}}\right) = \xi^{-n} \left(\frac{R_H}{\ell_{\rm P}}\right)^{-\lambda_{\rm struct}}, \tag{13}$$

showing that κ is suppressed by both the ratio $\ell_{\rm P}/\ell_g$ and by the structural-damping factor that already appears in the dark-energy sector.

For $\lambda_{\rm struct}$ in the range needed to match ρ_Λ, and for ℓ_g well above $\ell_{\rm P}$, one naturally expects κ in the range 10^{-7}–10^{-5}, small enough to be consistent with current Casimir data, yet possibly detectable with future improvements.

6 Experimental constraints from Casimir measurements

State-of-the-art Casimir experiments, using sphere–plate or plate–plate configurations, have measured the Casimir force with relative precision at or below the 10^{-3} level over distances of order $d \sim 100$–$1000\,\text{nm}$. Translating these results into bounds on $\delta_{\rm gran}(d)$, we require

$$|\delta_{\rm gran}(d)| = |\kappa| \left(\frac{d}{\ell_g}\right)^n \lesssim 10^{-2}\text{–}10^{-3} \tag{14}$$

in order to remain within experimental uncertainties.

Adopting representative values $n \simeq 1$ and $\kappa \sim 10^{-6}$, we obtain a conservative lower bound on the granule scale,

$$\ell_g \gtrsim 10^{-19}\,\mathrm{m}, \tag{15}$$

for separations d in the few hundred nanometer range. This is well above the Planck length but well below current direct experimental access, which is precisely the regime where a granular vacuum could be physically meaningful without having been detected yet.

Further improvements in experimental precision, especially at larger separations where the relative correction grows as $(d/\ell_g)^n$, could either detect this deviation from Eq. (1) or push ℓ_g to even smaller values, progressively closing the window for vacuum granularity in the GCV sense.

7 Future laboratory tests of vacuum granularity

Several experimental strategies can significantly sharpen the bounds on ℓ_g and κ:

- **Cryogenic Casimir measurements:** Operating at temperatures $T \lesssim 4\,\mathrm{K}$ reduces thermal noise and systematic errors, allowing relative precision $\Delta F/F \sim 10^{-4}$. For $d \sim 500\,\mathrm{nm}$, this would probe ℓ_g down to $\sim 10^{-20}\,\mathrm{m}$ for κ in the 10^{-6} range.
- **Superconducting resonators:** Embedding a Casimir cavity in a superconducting microwave resonator allows extremely precise measurements of force-induced frequency shifts. Sensitivity at the 10^{-5} level or better would significantly tighten existing bounds.
- **"Casimir-less" configurations:** By choosing materials and geometries for which the standard Casimir contribution cancels or is strongly suppressed, any residual force would be a clean probe of $\delta_{\mathrm{gran}}(d)$.
- **Large-radius sphere–plate setups:** Using a sphere of radius $R \gg d$ enhances the effective interaction area and amplifies small deviations from the d^{-4} law as the separation is varied.

These approaches are realistic extensions of current technologies and can be designed to specifically target the $(d/\ell_g)^n$ dependence predicted by Eq. (12).

8 Consistency with gamma-ray attenuation

Paper 4 showed that high-energy gamma rays propagating through the granular vacuum of P_2 suffer an additional, small attenuation on top of standard $\gamma\gamma$ pair production with the extragalactic background light (EBL) and cosmic microwave background (CMB). The observed flux from a source at redshift z is

$$F_{\mathrm{obs}}(E, z) = F_{\Lambda\mathrm{CDM}}(E, z)\,\Gamma(D_L(z), E, \gamma_N), \tag{16}$$

where $F_{\Lambda\mathrm{CDM}}(E, z)$ is the standard prediction including EBL and CMB attenuation, $D_L(z)$ is the luminosity distance, and

$$\Gamma(D, E, \gamma_N) = \exp\left[-\gamma_N \left(\frac{D}{\ell_g}\right)^{\alpha} \left(\frac{E}{E_0}\right)^{\beta}\right] \tag{17}$$

is the extra damping factor, with $\gamma_N \ll 1$ and $\alpha, \beta > 0$.

The key point is that the same granule scale ℓ_g appears in both the Casimir correction and gamma-ray attenuation. Laboratory bounds on ℓ_g therefore imply bounds on the combination $\gamma_N D^\alpha E^\beta$ that can be tested against gamma-ray data from Fermi-LAT, HESS, MAGIC, VERITAS and CTA. Conversely, any evidence for non-zero γ_N from astrophysical data would imply a minimal granule scale that could be confronted with Casimir measurements.

This synergy makes the GCV hypothesis quantitatively testable across very different regimes: sub-micrometer laboratory distances and gigaparsec astrophysical baselines, both governed by the same underlying granular structure of the vacuum.

9 Discriminating GCV from other new-physics scenarios

Several alternative scenarios also predict deviations from the standard Casimir force:

- **Large extra dimensions (ADD models):** Additional compact dimensions modify gravity at short distances, typically leading to corrections that scale as d^{-2-p} for p extra dimensions, rather than the d^{n-4} scaling of Eq. (12).
- **Light scalar fields and moduli:** Exchange of light scalar particles produces Yukawa-type corrections $\propto \exp(-md)$, again distinct from a pure power-law in d.
- **Superstring-motivated branes:** Higher-dimensional branes and their excitations can induce corrections, but these depend on compactification details and generally differ in both form and parameter dependence from the GCV prediction.

In the GCV model, the deviation from the standard Casimir law is directly tied to the granule scale ℓ_g and to the structural-damping exponent that also controls dark energy and membrane pressure. The predicted correction is a simple multiplicative factor with a clean power-law dependence on d/ℓ_g. Observation of such a scaling would strongly favor a classical granular-vacuum origin rather than extra dimensions or superstring dynamics.

10 Conclusion

We have developed a detailed analysis of how vacuum granularity in the Granular Cosmic Vacuum framework modifies the Casimir effect and how such modifications can be used as precision laboratory probes of the same deep structure that underlies dark energy, dark matter, and high-energy gamma-ray attenuation.

The main results are:

- The intergalactic domain P_2 is modeled as a granular medium made of microscopic white holes connected by contracted temporal strings. The lattice spacing ℓ_g defines a fundamental length scale of the vacuum.
- This granularity discretizes the k-space spectrum of electromagnetic modes between Casimir plates, leading to a corrected force

$$F_{\text{total}}(d) = F_{\text{Cas}}(d) \left[1 + \kappa \left(\frac{d}{\ell_g}\right)^n\right],$$

with structural exponent $n > 0$ and small amplitude $\kappa \ll 1$.

- The amplitude κ is directly related to the Planck tension T_{P}, the cosmic tension T_{cosmic} that yields dark energy, and the structural-damping parameter $\lambda_{\mathrm{struct}}$. Casimir corrections are thus part of the same unified GCV structure that explains the dark sector.
- Existing Casimir experiments constrain $\ell_g \gtrsim 10^{-19}\,\mathrm{m}$ for typical parameter choices, consistent with but not yet excluding a granular vacuum. Future cryogenic and superconducting-resonator experiments can significantly tighten these bounds.
- The same granule scale ℓ_g appears in the gamma-ray attenuation factor derived in Paper 4, allowing cross-checks between laboratory data and high-energy astrophysical observations.
- All strings and membranes in the GCV are classical four-dimensional geometric structures, not superstrings or higher-dimensional branes. Their physical effects, including Casimir corrections and gamma-ray attenuation, arise from geometry and tension, not from quantum string excitations.

In summary, the Casimir effect offers a powerful, controllable, and conceptually clean way to test whether the vacuum is truly smooth or has a granular structure as proposed in the GCV framework. When combined with high-energy gamma-ray data, it provides a coherent experimental program to probe the deep structure of spacetime using both laboratory and astrophysical observations.

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